IAF-93-Q.4.409

GRAZ AUSTRIA
1 9 9 3

THE MAGELLAN VENUS MAPPING MISSION: AEROBRAKING OPERATIONS

by

Daniel T. Lyons
R. Stephen Saunders
Douglas G. Griffith

Jet Propulsion Laboratory,
California Institute of Technology,
Pasadena, CA, USA, 91109

44th CONGRESS OF THE
INTERNATIONAL ASTRONAUTICAL FEDERATION
October 16–22, 1993 / Graz, Austria

THE MAGELLAN VENUS MAPPING MISSION: AEROBRAKING OPERATIONS

by

Daniel T. Lyons[1]
R. Stephen Saunders[2]
Douglas G. Griffith[3]

Jet Propulsion Laboratory,
California Institute of Technology,
Pasadena, CA, USA, 91109

The orbit of the Magellan spacecraft was circularized during a 70 day aerobraking phase, which ended on August 3, 1993. Shrinking the orbit apoapsis from 8467 km down to 541 km was required to obtain meaningful gravity science data at high and moderate latitudes. Aerobraking was the only way to reach this nearly-circular orbit, since the amount of propellant on board Magellan was at least an order of magnitude too small to circularize propulsively. This paper will describe the steps taken by the Magellan Flight Team to successfully aerobrake the Magellan spacecraft into the nearly-circular orbit. Magellan is currently in a 541 by 197 km altitude orbit around the planet Venus. This paper will briefly describe the Magellan mission history and hardware, the goals of the continuing Magellan mission, the exciting aerobraking phase, and other science objectives beyond the primary goal of producing a high-resolution global-gravity map of Venus.

Magellan Mission Description

The Magellan Mission is almost over. The primary mission objective to map the surface of Venus has been completed, with 98% of the surface imaged at least once by a Synthetic Aperture Radar (SAR), which doubled as a radiometer. A second antenna mapped the altimetry of 98% of the surface in parallel with the SAR imaging. The plane of the Magellan orbit remains nearly inertially fixed while the planet rotates beneath periapsis once every 243 days. Three 243 day mapping cycles were devoted to the radar experiment, so some regions have been imaged three times at different incidence angles. No further radar data will be collected due to telecom problems. The fourth 243 day cycle was devoted to mapping the gravity field, Periapsis was lowered into a ±6 km zone centered on 175 km for the Cycle 4 gravity map. This periapsis altitude was low enough that atmospheric densities could be measured by both the navigational tracking and the attitude control perturbations. Although gravity data can be obtained from the entire orbit when the Sun geometry permits, the elliptical orbit geometry limited the high resolution gravity data to a ± 30° latitude band centered on periapsis.

[1] Member of Technical Staff, (818) 393-1004
[2] Magellan Project Scientist,
[3] Magellan Project Manager, (818) 393-0693

The research described in this paper was carried out at the Jet Propulsion Laboratory, California institute of Technology, under a contract with the National Aeronautics anti Space Administration.

l-able 1: Representative Orbital Element Samples relative to Venus Mean Equator of 1985 IAU Ref.

	Start of Cycle-1 SAR Mapping	Start of Cycle-4 Equatorial Gravity	Post Aerobraking Global Gravity
Epoch .	August 24, 1990	September 14, 1992	August 5, 1993
Semi-Major Axis (km)	10,425.045	10.384.842	6,418.7
Eccentricity	0.391795	0.399857	0.025333
inclination (deg.)	85.5°	85.5°	85,4°
Node (deg.)	-61.4°	-61.7"	-61.8°
Arg. Peri. (deg.)	170.4°	169.3°	169.0°
Apoapsis Alt. (km)	8,458.5	8,486.3	541.0
Periapsis Ait. (km)	289.6	181.4	197.0
Period (seconds)	11,734.1	11,666.3	5,669.0

Obtaining a global, high-resolution gravity field from the nearly-circular, post-aerobraking orbit is essential for understanding the internal geophysics of Venus.

The Magellan spacecraft is currently in a nearly-circular, 94.5 minute orbit around Venus. The orbit is still inclined 85.5° to the Venus equator, and made the entire surface visible to the spacecraft radar at some time during the mission. Now that the orbit is nearly-circular, Venus gravity will drive the latitude of periapsis much further north and south (+28° N to +4° N) than during the prime mission when periapsis could oniy drift by one or two degrees from 10° N. The periapsis altitude fluctuations will aiso increase from 15 km per cycle for the prime mission to 75 km for the post-aerobraking orbit, Although the nodal precession aiso increases for the post-aerobraking orbit, the node decreases by iess than a degree per cycle even for the post-aerobraking orbit. The evolution of the nearly-circular orbit is described in detail in Reference 1. During the recently compieted 70 day Aerobraking phase, aerodynamic drag lowered the orbit apoapsis by 113 km per day, while periodic maneuvers maintained the periapsis in a 1 km corridor which gradually decreased from 141 km to 136 km. (Ref. 2 & 3) Aerobraking was terminated by raising periapsis to 197 km using a series of five 12.4 km maneuvers. Gravitational perturbations will quickly pull periapsis back down into a ± 20 km corridor centered on 175 km.

The minimum period of the nearly-circular orbit was constrained by a power requirement to fully recharge the batteries during the long, frequent solar occultations. The solar paneis were sized for the primary-mission mapping-orbit, where the time available for recharging was a much larger fraction of the orbit. The solar paneis are shown in Figure 1, which illustrates the Magellan spacecraft configuration.

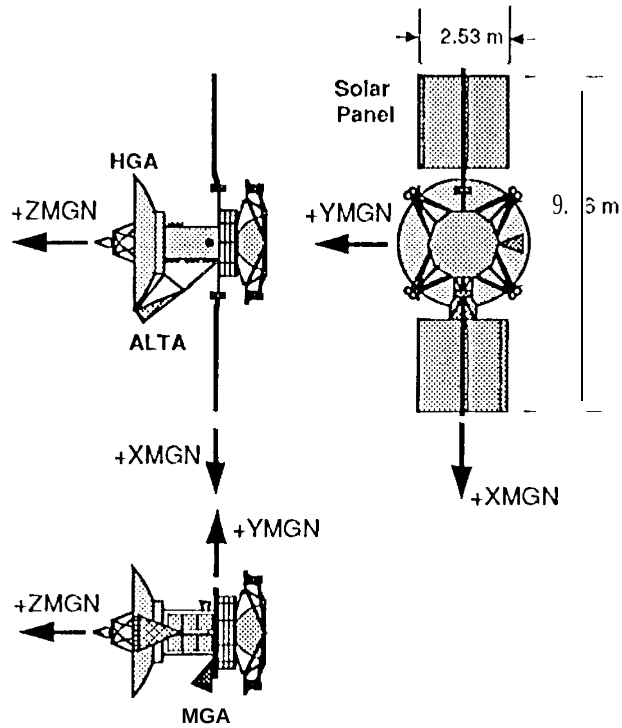

Figure 1. The Magellan Spacecraft Configuration.

Magellan is a 3-axis stabilized spacecraft which is normally controlled by three reaction wheels. Pairs of 0.9 N thrusters on booms near the -Z end of the spacecraft are used for propulsive orbit trim maneuvers and for unloading the momentum which accumulates in the reaction wheels. A 3.7 meter high gain antenna is rigidly attached to the + Z end of the spacecraft. The high gain antenna is used for telecom and was used as the radar antenna during SAR mapping. An altimeter antenna is mounted next to the high-gain-antenna. A medium gain antenna is mounted on the -Y side of the spacecraft, while a dual V-slit star scanner is mounted on the +Y side. The forward equipment module is located between the bus and the high-gain antenna and contains the reaction wheels, transmitters, batteries, gyros, and the radar transmitter and electronics. The ten-sided bus contains the attitude control computers, sequencing computers, shunt regulator electronics, tape recorders, and star scanner electronics. A pair of single-degree-of-freedom solar panels are mounted on the +X and -X sides of the spacecraft. Because the solar panels are the only external moving parts, the entire spacecraft must be reoriented to sweep the star scanner across stars, or to point the high gain antenna at Earth or Venus.

Continuing Mission Objective: High-Resolution Global-Gravity Science

The primary reason for continuing the Magellan mission is to obtain a high-resolution global-gravity field for Venus, especially at the high latitudes which were poorly resolved during the Cycle 4 gravity mapping phase. The only way to achieve the low altitudes at all latitudes which are required by the global-gravity experiment was to aerobrake the spacecraft into a nearly-circular orbit. The global gravity mission phase began August 3, 1993, and will continue until nearly global coverage is achieved in mid-October, 1994. Almost two full 243 day cycles are required to obtain the global gravity because Superior Conjunction and occultations of the Earth by Venus put gaps in the data. References 4 and 5 describe Venus gravity fields which have been produced using Magellan and Pioneer Venus Orbiter data. Even newer models are in use by the Magellan project. Once all of these Venus gravity data sets are combined and correlated with the topographic maps produced from the Magellan altimetry and Synthetic Aperture Radar data, geologists and planetologists will be able to infer the types of interior processes, such as isostatic adjustments to loads, dynamic support, and other interior processes which may be related to various surface features (Ref. 5). Venus gravity anomalies have been shown to be highly correlated with Venus topography (Ref. 6). The higher resolution, global gravity data set which is being obtained from the post-aerobraking phase will significantly increase the ability of scientists to correctly model mantle convection and lithospheric compensation mechanisms which modify the surface features on Venus (Ref. 7,8, 9).

What is Aerobraking ?

Aerodynamic drag was the only means available for Magellan to reduce the orbital speed at periapsis by the 1,300 m/see required to reduce the apoapsis altitude from 8,500 Km to 541 Km, which reduced the orbital period from 3.26 hours to 1.58 hours. Propulsively circularizing the orbit would have required an order of magnitude more propellant than was on-board, not to mention some means of delivering that much propellant to Venus. Aerobraking required three phases:

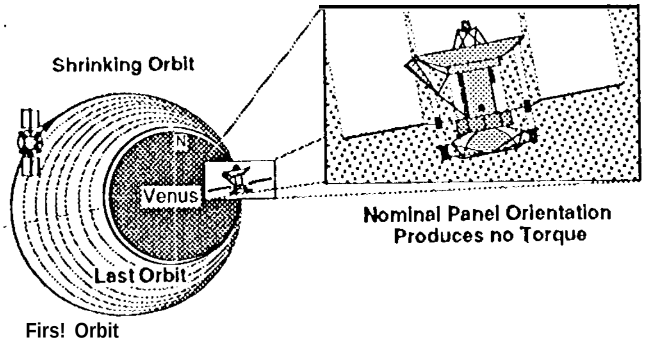

Figure 2... Incredible Shrinking Orbit.

WalkIn Phase:

A "walk-in" phase was necessary to lower the periapsis into the outer fringes of the atmosphere at the beginning of Aerobraking because' the uncertainty in the average density was very large. The planned corridor at the start of the Aerobraking phase was expected to be at about 140 Km, well below the lowest altitude (150 Km) at which the majority of actual density measurements had ever been made. The corridor design allowed for a 30 " atmospheric variability of about 400/. during the main phase with no "hidden" safety margin, and was large enough for the expected fluctuations in the atmosphere but not large enough to account for a 1009'o uncertainty in the mean. The 2 km difference shown in Figure 3 between the periapsis altitude for the final plan prior to the start of aerobraking and the actual periapsis altitude is primarily due to the difference between the most conservative (most dense) available atmosphere model and the actual density. The on-board Corridor Orbit Trim Maneuvers used for the "walk-in" phase and the main phase cause the step changes in the periapsis altitude, including the three n-aneuvers" used 'to Transition from 150 km down to 40 km at the start.

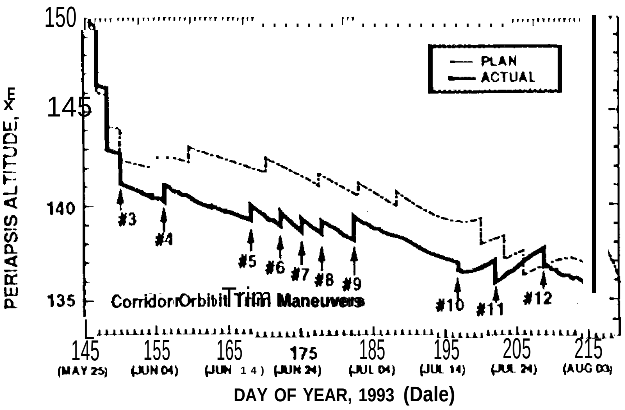

Figure 3. Planned and Actual Periapsis Altitudes.

Main Phase:

The purpose of the main phase is to keep periapsis in a well defined periapsis corridor during the 67 day "Main" phase. The small (0.17 m/sec) propulsive maneuvers controlled periapsis altitude to be high enough to avoid excessive aerodynamic heating, yet low enough for the drag to gradually lower the periapsis speed in a reasonably small number of days (2 m/see / orbit for the 70 day aerobrake duration). For all orbits below 150 km (except one), the spacecraft passed through the atmosphere in a "tail-first" attitude with the maximum solar panel area (backside) exposed to the flow. This attitude was not only aerodynamically stable, but also maximized the exposed surface area (24 m^2) and thus minimized total duration. During the early stages of planning for aerobraking, two issues constrained the lowest periapsis altitude: the maximum heating rate which could be tolerated by the surface materials and the maximum dynamic pressure which could be accommodated by the Attitude Control System. Although temperature ultimately became the limiting factor, much of the early planning was based on a dynamic pressure constraint which guaranteed that the spacecraft would not lose attitude knowledge in the event that fault protection had put the spacecraft into a coning search for the Earth which resulted in a sideways atmospheric entry. Because the dynamic pressure constraint had been so thoroughly analyzed and was well understood, dynamic pressure was used for defining one side of the corridor. Heating rate could also have been used to trigger corridor control maneuvers, however, the surface temperatures were strongly influenced by the solar aspect angle and the effects of Venus albedo, which both changed during the planned 80 day aerobraking phase.

As aerobraking proceeded, the actual heating measured by the thermocouples on the solar panels was much less than that expected for a thermal accommodation coefficient of unity (i.e. all of the kinetic energy of the collision being absorbed by the panels). The dynamic pressure limit (and thus the heating rate) was increased from 0.32 to 0.35 N/m^2 to shorten the aerobraking duration by taking advantage of the observed lower heating. In fact, the aerobraking duration could have been shortened even more except that the only Star Pair . which was available during the third quarter of aerobraking would be blocked from view by Venus if the orbit period were allowed to shrink below 102 minutes prior to July 27. Thus the duration of the aerobraking phase was constrained by star pair availability more than by any other factor. Star pair availability also put a hard limit on the last day available for aerobraking (August 16), when the only visible star pair had to be scanned at periapsis, which required that periapsis be well above the atmosphere.

The Venus gravity field tended to pull the periapsis altitude lower, so most of the corridor control maneuvers were to raise periapsis and thus lower both the heating rate and dynamic pressure. Three maneuver sizes, which could either raise or lower periapsis, were stored on-board. Although the actual maneuver parameters which remained constant during aerobraking were the durations of the burns, the approximate delta-V sizes which could be enabled by a simple, off-the-shelf ground commands were approximately 0.17, 0.34, and 0.68 m/sec.

Endgame:

The endgame phase was much more complicated than simply raising periapsis out of the atmosphere to stop aerobraking when the apoapsis altitude has reached the target value (541 Km). As the period became shorter and the drag pass became longer, less time in each orbit was available for telemetry readout, so the sampling rate had to be reduced, and the multiple readouts had to be eliminated. The period available for commanding the spacecraft also became shorter, causing some commands file uploads to be split across multiple orbits. The periapsis altitude of the orbit became much more sensitive to gravitational perturbations during the endgame. As the duration of the pass through the atmosphere grew rapidly during the endgame, the thruster activity for attitude control started to have a more noticeable effect on the altitude of periapsis, which in turn made accurate prediction of the time of periapsis much more difficult. The decay in the periapsis altitude also became much larger as the orbit became more circular. The only pair of stars which were visible when the spacecraft was not in the "tail-first" attitude had to be scanned immediately after exiting the atmosphere. Thus the endgame officially began when the looper was reconfigured to use the final star pair on July 27, 1993. Adjustments to the table of predicted periapsis times were made as often as twice per day during this endgame phase. Margins were increased near the end because larger atmospheric fluctuations were expected on the nightside.

Activities On-board the Spacecraft

Figure 4 shows the activities which occurred on-board the spacecraft. The Magellan spacecraft used a stored sequence of absolute time-tagged events to control activities during cruise and SAR mapping. In order to reduce operations costs, the Magellan project took advantage of the repetetivenesss of events and developed a controlling sequence for the gravity mapping in Cycle 4 which was an "infinite loop" that would run indefinitely. This looping strategy was adapted to the aerobraking phase by using a four orbit pattern which not only repeated over and over, but which linearly decreased the time allocated to each orbit before beginning the next orbit. The typical activities controlled by the "looper" during aerobraking will be described next.

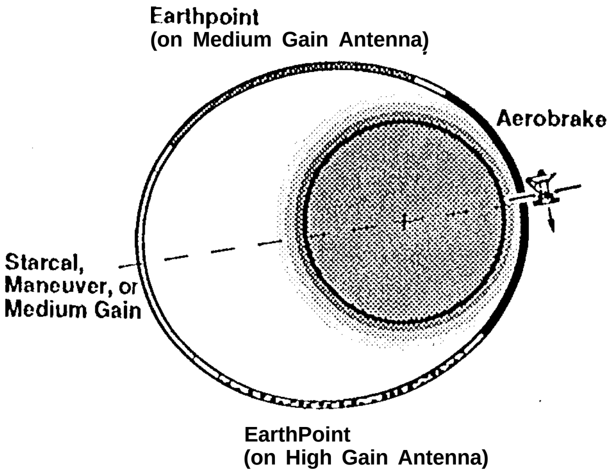

Figure 4. Aerobraking Orbital Activities.

Just prior to entering the atmosphere on each orbit, the spacecraft turned to the tail-first attitude using reaction wheels to save propellant. 1 he spacecraft switched from a very precisely specified (0.01 0, reaction wheel control law to a very loosely specified thruster control law for the pass through the atmosphere. Switching to a thruster control law with a ± 10° deadband enabled large timing errors to be accommodated by the existing control system, and thus avoided a costly redesign of the flight software. After emerging from the atmosphere, the thruster control law dead band was tightened up to damp out pointing and angular rate errors prior to switching back to reaction wheels.

The spacecraft then turned using the reaction wheels to point the high gain antenna toward the Earth so that the stored Aerobraking telemetry could be sent to Earth for analysis. Unfortunately, when the high gain antenna was pointed at Earth for the dates available for aerobraking, the Sun was shining directly on the side of the spacecraft. Because the thermal properties of the spacecraft had degraded to the point where twice as much solar energy was being absorbed than allocated for the prime mission, some components of the spacecraft would overheat when exposed to full solar illumination for more than tens of minutes per orbit. Thus, the Magellan spacecraft was forced to turn away from the high gain to Earth attitude, which could transmit data at the maximum 1200 bits/see, and use the high gain antenna as a solar shade. Fortunately, the dates available for aerobraking allowed the high gain antenna to be pointed in the general direction of the sun while simultaneously allowing the medium gain antenna to be pointed at the Earth. Although the medium gain "hide attitude" enabled a 40 bit/see telemetry data rate, it also enabled much longer tracking arcs which improved the accuracy of the Navigation solutions required to control the periapsis timing and altitude.

The duration of the Medium gain to Earth "hide" interval was shortened autonomously every orbit to account for the shrinking orbit period. The Medium gain to Earth interval was also interrupted by star scans and corridor control propulsive maneuvers to raise or lower the periapsis altitude. Star scans to update the attitude knowledge using the body fixed, V-slit star scanner were performed every other orbit by reorienting the entire spacecraft through a series of three attitude maneuvers. Corridor control propulsive maneuvers to raise or lower the periapsis altitude could be enabled on any non-star scan orbit, however, only 12 such maneuvers were used out of 730 orbits.

The location of the star scan had to be moved from apoapsis to slightly after apoapsis when the first pair of stars could no longer be used. Although the shift in location was easily implemented by changing a parameter, the location of the star scan had to be closely monitored, especially so as the location of the star scan moved closer to Venus as the apoapsis altitude decayed. When the third and final star pair became available, the order of events had to be rearranged to put the star scan immediately after the pass through the atmosphere, which required loading a new "looper", killing the old one and starting the new one at just the right time. The duration of the high-gain to Earth activity had to be shortened to allow sufficient time to hide from the Sun cm each orbit.

Activities On the Ground

Figure 5 shows a typical "Day in the Life" during aerobraking. Planned activities began at 5 am pacific time and ended at 6 pm. The upper branch shows the planning, tracking, and management decision flow required to understand the current spacecraft status and plan future activities such as orbit trim maneuvers, and star pair swaps. The lower branch shows the flow required to generate commands which are sent to the spacecraft to keep the looping sequence close to reality, enable orbit trim maneuvers, control data rates, and change on-board parameters. Near the beginning of aerobraking, commands were sent to the spacecraft about 4 times per week, so there were some non-commanding days, euphemistically known as "The Other Day", which were not quite as hectic as the typical day shown in the figure. About two thirds of the way through aerobraking, everyday became a command day. During the last two weeks of aerobraking, the spacecraft often had to be commanded twice per day in order to keep the looping sequence activities within acceptable bounds.

Carefully planning, coordinating, and scheduling the daily activities prior to the start of aerobraking was an essential part of the aerobraking success.

Aerobraking Data

I-he following figures' show telemetry or tracking derived data from the Magellan aerobraking phase and illustrate what happened during aerobraking.

Figure 6, which is typical of all aerobraking orbits, shows the X-axis attitude error during the last aerobraking pass through the atmosphere. The attitude error is the difference between the actual attitude and a time varying reference attitude which was specified by the 8th order polynomials used during SAR mapping. The X-axis was orthogonal to the orbit plane, so timing errors cause the X-axis component of the reference attitude to diverge from

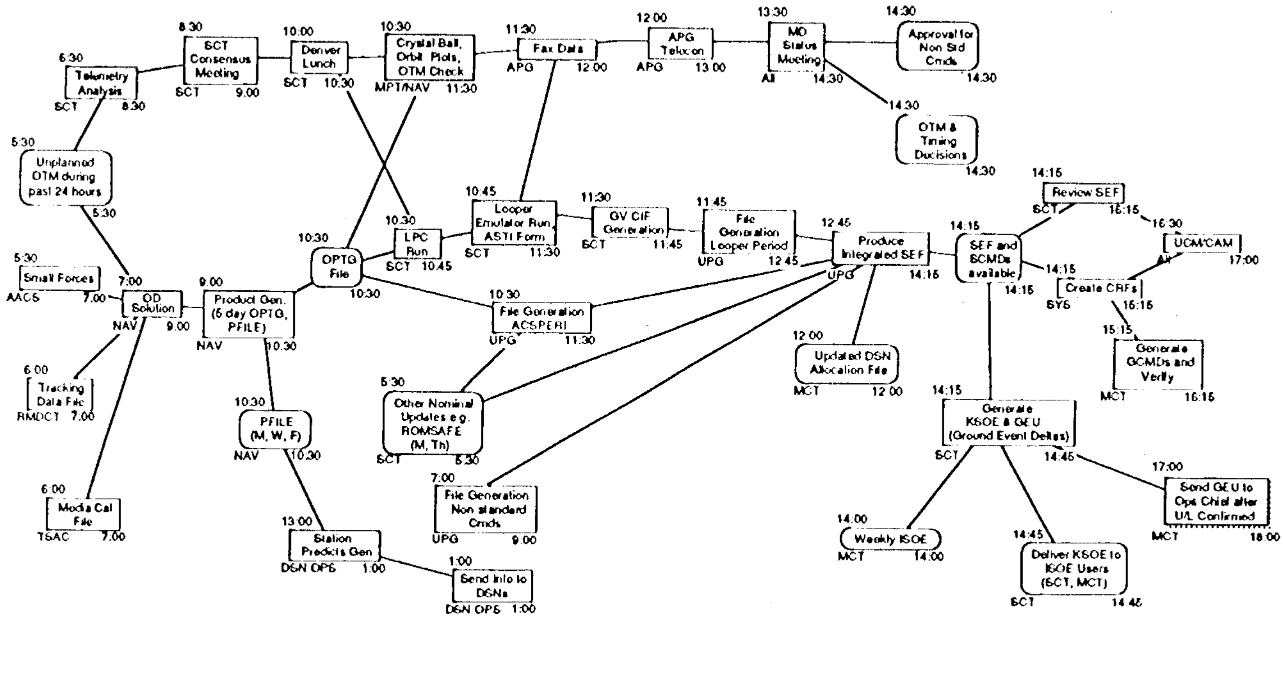

Figure 5. Ground Activities: A "Day in the life"

the desired “tail-first” attitude. The plot begins when the spacecraft switches from reaction wheel to thruster control. Since the reaction wheels have a slight residual momentum which is transferred to the body as the reaction wheels spin down, the body slowly drifts away from the desired attitude. When the deadband is reached, the thrusters fire to keep the attitude error within the deadband, and the attitude error has a sharp corner. The angle of attack could be anywhere in the ±1 0° deadband by the time the sensible atmosphere was entered. (The 10° deadband is defined relative to “control-axes”, which are rotated 45° about the Z-axis relative to the body axes shown in Figure 1 and plotted in the Figure 6.) The angle of attack produced an aerodynamic torque which forced the attitude toward the aerodynamic null. Since the system had no damping, the vehicle oscillated around the null point with a frequency which increased and an amplitude which decreased as the vehicle approached the maximum dynamic pressure at periapsis. The null point in the figure is not at zero degrees, due to the difference between the predicted time of periapsis and the actual time of periapsis for this particular orbit. Updating the periapsis time table reset the timing error and the null offset to zero, however, the null offset would drift away from zero as the timing errors increased. This null offset provided a very accurate means to measure the timing error from the nearly real time telemetry data. Future aerobraking mission operations of aerodynamically stable spacecraft could be greatly simplified by using this null offset to update the time of periapsis autonomously, rather than using ground-based navigation data to predict a periapsis time table which must be checked, approved, and uplinked.

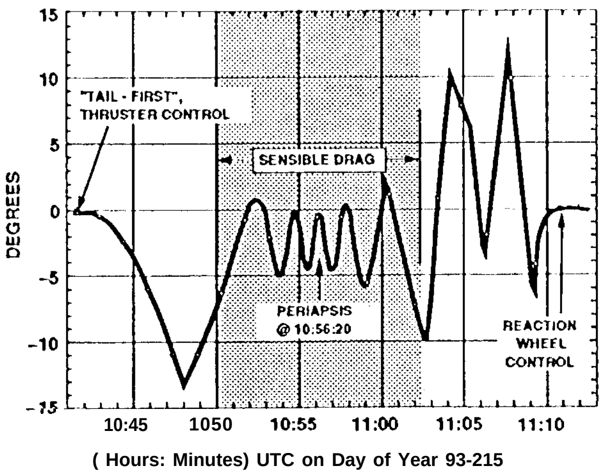

Figure 6. X-Axis Attitude Error

The residual rate remaining when the vehicle left the atmosphere caused the vehicle to drift to the deadband and essentially bounce from one side of the deadband to the other, because the control law had no damping. Since the only propellant expended when on thruster control occured when the spacecraft was not actually in the atmosphere, the amount of propellant required could have been reduced to practically nothing by designing the appropriate control system. The project had no resources available to redesign and test new control laws, but did have sufficient propellant margin, so the optimum solution was to use some propellant and adapt the existing control law to the completely new control environment. As experience was accumulated during aerobraking, propellant use was reduced by predicting the time of periapsis more accurately and reducing the time spent on thruster control.

Figure 7 shows the Dynamic Pressure for every orbit as reconstructed by the Nav Team from the inferred effects of drag on the orbit. Most of the oscillation is due to fluctuations in the atmosphere of Venus. Some of the larger jumps are due to maneuvers which change the periapsis altitude, and thus change the density and dynamic pressure on the next orbit. Pioneer Venus Orbiter data indicated that the 10 density variation would be about 12% on the dayside, so the plan was to raise periapsis whenever the average dynamic pressure (as defined by an 11 orbit running mean) became greater than 0.32 N/m^2, which was expected to result in an 80 day aerobraking duration. (Aerobraking started on the dayside at 10 am local solar time.) As we approached the 0.32 N/m^2 value for the first time, temperature measurements on the solar panels indicated that the actual heating was less than expected and the observed density fluctuations were about half the expected value, so the “trigger” point was increased to 0.35 N/m^2 prior to the first corridor control maneuver. The trigger was reduced

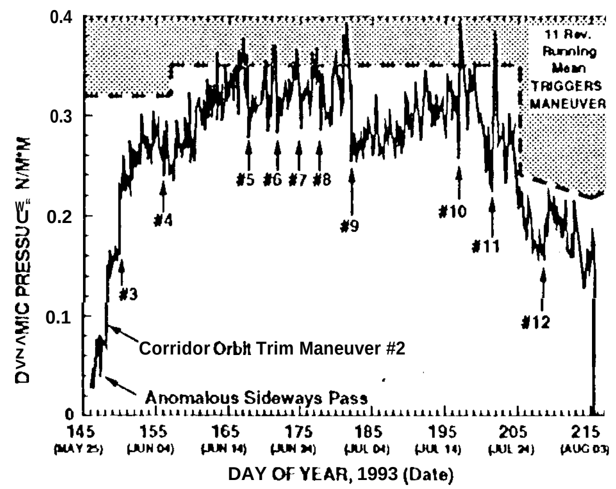

Figure 7. Dynamic Pressure History and Maneuver Trigger Threshold.

to 0.20 N/m^2 during endgame as the orbit approached the terminator, because the Pioneer Venus Orbiter data showed the 10 daily fluctuations increased to 500/. on the nightside. The Magellan spacecraft stopped aerobraking at about 6 pm local solar time, and did not experience a significant increase in the atmospheric fluctuation.

Figure 8 shows the temperature of one of the four thermocouples which were embedded in the two solar panels. Note that the maximum temperature for this typical orbit only reaches about 75 "C while in the atmosphere. The maximum slope occurs at periapsis where the heating rate is a maximum. The peak temperature occurs about the time that the aerodynamic heating reaches zero, due to the time lag caused by the thermal mass of the solar panel. (The thermocouple was attached to the side of the panel away from the flow, so the heat had to soak through the panel to reach the sensor.) Reaching the temperature limit of 110 "C would have caused the project to immediately command a periapsis raise maneuver, because the possibility of a 30 density spike on the next orbit would overheat the solar panels and the high gain antenna. The maximum panel temperature during aerobraking was only 89 "C, so an emergency periapsis raise maneuver was never even discussed once aerobraking had begun. The solar panels normally run at 100 "C when pointed at the Sun. The temperatures increase after leaving the atmosphere (right side of the figure) when the panels are reoriented to point at the Sun to collect power.

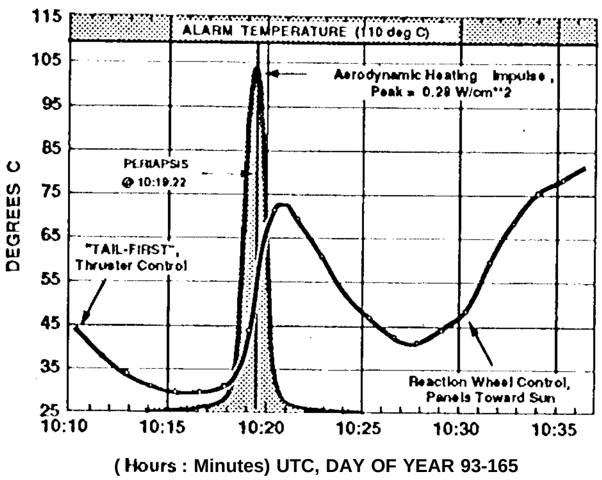

Figure 8. Solar Panel Temperatures

Figure 9 compares the actual decrease in the apoapsis altitude (solid line) with the the baseline plan produced just before aerobraking started (dashed line). Although aerobraking was a very exciting and hectic phase of the mission, the aerobraking phase followed "the plan" very closely.

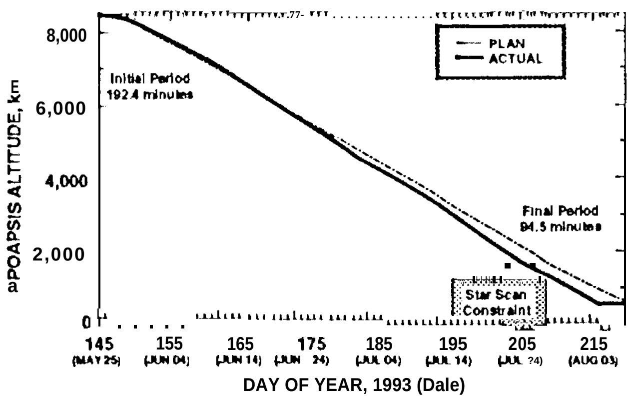

Figure 9. Planned and Actual Apoapsis Altitudes

Conclusions

The Magellan Mission has demonstrated that the aerobraking technique can be safely used to remove energy from spacecraft orbiting planets with atmospheres. Immediate applications to the next orbital missions to Mars are currently under consideration. The lessons learned from Magellan will enable significant cost savings for these future aerobraking missions because less propellant mass will be needed, so less expensive launch vehicles can be used.

I-he immediate benefit of aerobraking Magellan is that a high-resolution, global-gravity field for Venus can now be measured. Such a high-resolution, global-gravity field will significantly enhance the science return from the Magellan Mission by enabling geophysicists and planetologists to infer the interior geodynamics of Venus. The only way to achieve the nearly-circular orbit that is required for global gravity science was to aerobrake the spacecraft.

Other opportunities for collecting science data from the current nearly-circular orbit have been identified, and are being pursued on a best level of effort basis by the remaining members of the Magellan flight team. Some of the proven data types which can be collected include: Radio Occultation data, Atmospheric Science data, Bistatic Radar data, and Particle Surface Interaction data.

Acknowledgements

1 he authors wish to acknowledge the tremendous effort expended by the spacecraft team at Martin Marietta Astronautics Group in Denver Colorado, the navigation and mission control teams at the Jet Propulsion Laboratory, and the Deep Space Network around the world. The NASA Ames and Langley research centers also made significant contributions to the planning phase of the mission.

References:

1) D.T. Lyons, W.L. Sjogren, R.A. Lock, and R.S. Austin, "Beyond Aerobraking: Designing the Magellan Global Gravity Experiment", paper # AAS 93-656, AAS/AIAA Astrodynamics Conference, Victoria, B.C. Canada, August 19-22, 1993.

2) D.T. Lyons, W.L. Sjogren, W.T.K. Johnson, D. Schmitt, and A. McRonald, "Aerobraking Magellan", paper # AAS 91-420, AAS/AIAA Astrodynamics Conference, Durango Co., August 19-22, 1991.

3) R.A. Cook, and D.T. Lyons, "Magellan Aerobraking Periapse Corridor Design", paper #AAS 92-159, AAS/AIAA Space flight Mechanics Meeting, Colorado Springs, Co., February 24-26, 1992.

4) J.B. McNamee, G.R. Kronschnabl, S.K. Wong, and J.E. Ekelund, "A Gravity Field to Support Magellan Navigation and Science at Venus", Journal of the Astronautical Sciences, Vol. 40, No. 1, January-March 1992. pp. 107-134.

5) Sean C. Solomon, "1 he Geophysics of Venus", Physics Today, Vol. 46, No. 7, July 1993.

6) W.L. Sjogren, R.J. Phillips, P.W. Birkeland, and R.W. Wimberly, "Gravity Anomalies on Venus", Journal of Geophysical Research, 85, 8295-8302, 1980.

7) W.L. Sjogren, A.S. Konopliv, N. Borderies, M. Batchelder, J. Heirath, and R.N. Wimberly, "Venus Gravity: New Magellan Low Altitude Data", LPI Abstracts, 24th Annual Lunar & Planetary Science Conference, Houston, Texas, March 15-19, 1992.

8) R.R. Herrick, and R.J. Phillips, "Geological Correlations with the Interior Density Structure of Venus", Paper 92JE01498, Journal of Geophysical Research, Vol.97, No. E1O, October 25, 1992, pp. 16,017-16,034.

9) R.E. Grimm, and R.J. Phillips, "Anatomy of a Venusian Hot Spot: Geology, Gravity, and Mantle Dynamics of Eistla Region, Paper 92 JE01500, Journal of Geophysical Research, Vol.97, No, E1O October 25, 1992, pp. 16,035-16,054.

Acronyms

AACS	Attitude and Articulation Control System
ALTA	Altimeter Antenna
APG	Aerobraking Planning Group
ASTI	Advanced Sequence 1iming Information
CAM	Command Approval Meeting
DSN	Deep Space Network
GEU	Ground Event Update
GVCIF	Global Variable Command Input Form
HGA	t ligh Gain Antenna
ISOE	Integrated Sequence of Events
KSOE	Keyword Sequence of Events
l PC	Looper Period Calculator
MD	Mission Director
MCI"	Mission Control Team
MGA	Medium Gain Antenna
MPT	Mission Planning Team
NAV	Navigation Team
OD	Orbit Determination
OTM	Orbit Trim Maneuver
SAR	Synthetic Aperture Radar
SCT	Spacecraft Control Team
SEF	Sequence of Events File
UCM	Uplink Command Meeting
UPG	Uplink Group